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Bilateral teleoperation of mobile robots

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SUMMARY

A control structure for the bilateral teleoperation of mobile robots, with tactile feedback and visual information of the interaction force is proposed in this paper. Also an impedance controller is implemented in the mobile robot structure that guarantees the linear velocity be within a desired fixed range without saturation in the actuators. To illustrate the performance of the proposed control structure, experiments on a Pioneer 2 mobile robot teleoperated with a commercial joystick with force feedback are shown.

KEYWORDS: Teleoperation; Mobile robots; Impedance control; Force feedback; Sensors.

1. INTRODUCTION

The teleoperation of manipulators and mobile robots allows the human operator to "transfer" his/her capabilities and dexterousness into remote and sometimes hazardous environments, thus minimizing the associated risk level for personal injuries and equipment losses. In this sense, several control schemes and strategies for the teleoperation of mobile robots have been developed intended for an ample range of tasks such as land surveying in inaccessible or remote sites, transportation and storage of hazardous material, inspection of high-voltage power lines, deactivation of explosive devices, high-risk fire control, pesticide and fertilizer crop spraying and dusting, mining exploration and various other tasks.[1–4]

Mobile robots usually operate in *non-structured* environments, where the location of obstacles along the robot's intended trajectory is unknown, thus making it impossible to include them into the motion robot programming in order to avoid these obstacles. Consequently, mobile robots should face significant uncertainties regarding position and identification of objects along its trajectory. By considering the premise of uncertainty as the main problem to overcome, it may be inferred that the mobile robot has to be endowed with *sensorial interpretation* and *intelligence* capabilities.[1]

The main objective of this paper is to develop a simple system for the teleoperation of a mobile robot operating in a partially structured environment. To achieve this aim, two applications have been developed that run simultaneously (concurrently) in the work environment. One application drives the mobile robot in the partially structured environment and the other application is an interface between the joystick used for the teleoperation and its drivers. This application generates the reference signals for the remote mobile robot and the force effects on the joystick, so that the human operator "feels" the force that the remote robot exerts on the obstacles as it approaches them. Both applications use a shared memory to read and write the data being transferred between the local and the remote stations. Figure 1 shows a general layout of the proposed teleoperation system. Also, an impedance control structure[5,6] is proposed in the remote station for the mobile robot to avoid obstacles in its trajectory. The teleoperation system incorpo-

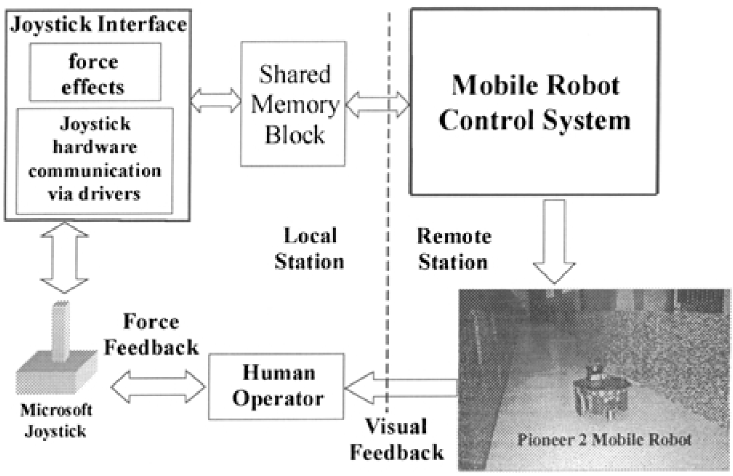

Fig. 1. Scheme of the developed teleoperation scheme.

rates a model of the human operator in the control loop,[6,7] and features the kinesthetic force feedback (tactile) and visual information of the interaction force of the mobile robot with the environment.[8–10]

The paper is organized as follows: Section 2 describes the advanced structure for bilateral teleoperation of a mobile robot. The mobile robot control system with its algorithm, are presented in Section 3. Section 4 deals with the joystick used for the teleoperation tasks. The experimental results are addressed in Section 5 while Section 6 summarises the conclusions.

2. ADVANCED CONTROL SYSTEM FOR BILATERAL TELEOPERATION OF A MOBILE ROBOT

This section describes in detail the proposed general control structure for a mobile robot teleoperation system with force feedback and impedance control at the remote site, including the dynamic model of the human operator who reacts to both stimuli.

Figure 2 shows the general structure for the advanced control of the proposed mobile robot teleoperation system. The *local system* presents two feedback loops: one corresponding to the tactile perception of the human operator and the other, the visual perception. The figure depicts as well the communication delays existing between the remote and the local stations. In this scheme, it is assumed that the fusion of both perceptions (visual and tactile) is done by weighing the two force sources performing the kinesthetic follow-up of the force. Therefore, the force generated by the *human controller* f_h is,

$$f_h = \rho f_{hf} + (1-\rho) f_{hv} \tag{1}$$

where: ρ represents the fusion coefficient of the visual and tactile channels, with $0 \leq \rho \leq 1$, and its value will be set according to the operating conditions of the teleoperation system, the difficulty degree of the task and the experience level of the human operator. Forces f_{hf} and f_{hv}, represent the arm forces of the human operator that react to tactile and visual stimuli, respectively. The combined force f_h, in Equation (1) will be the force done by the human arm remotely interacting with the environment through the mobile robot. The forces f_{hf} and f_{hv} are defined by,

$$f_{hf} = \left[\frac{K_{lf}}{(s+\delta)} (B_{ohf}\, s + K_{ohf}) \right] e_{freff} \tag{2}$$

$$f_{hv} = \left[\frac{K_{lv}}{(s+\delta)} (B_{ohv}\, s + K_{ohv}) \right] e_{frefv} \tag{3}$$

where K_{lf}, B_{ohf}, K_{ohf}, K_{lv}, B_{ohv}, K_{ohv} are the parameter matrices of the human operator's arm and δ indicates the location of the pole added to the human operator model included in the closed-loop. The tactile and visual errors e_{freff} and e_{frefv} are given by,

$$e_{freff} = f_{reff} - f_{em} \tag{4}$$

$$e_{frefv} = f_{refv} - f + f_{dv} \tag{5}$$

wher f_{reff} and f_{refv} are the reference signals of the local force and vision system, respectively; f_{em} is the force applied by the local manipulator on the human operator, f is the force exerted by the remote robot on its environment and f_{dv} is the visual mental reference of the human operator, with

$$-f_{em} = f_h + f + (M_h s^2 x_L) \tag{6}$$

Here, M_h is the mass of the human operator's arm and x_L is the location of the local robot (joystick or hand-controller). The force error of the local controller e_{fL} is given by,

$$e_{fL} = f_{df} - f_{em} - f^* \tag{7}$$

The controller of the local hand-controller (F. C.) is a PD-type force control which renders a force f_L to the motor which drives the local manipulator. The local hand-controller model can be linearized by taking into account

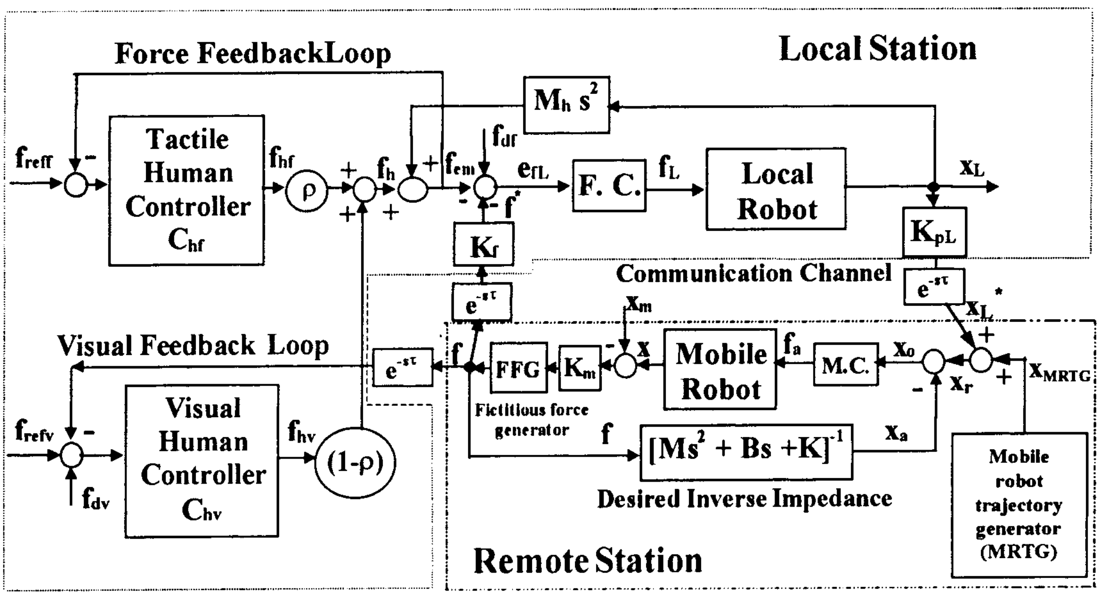

Fig. 2. Teleoperation control structure and mobile robot control system.

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the high speed-reduction ratio of the motors, its low inertia – e.g. a *joystick* type manipulator – the consequent high decoupling a and the low speed of motions generated by the human operator. The simplified local manipulator is then described as,

$$f_L = m_{rL}s^2 x_L^* + b_L s x_L^* \tag{8}$$

The position x_L^* of the local manipulator is the position reference for the remote system, after conditioning it by the position gain matrix K_{PL}. In the remote mobile robot system, there is an internal motion control loop and an external impedance control loop. The concept of mechanical impedance[5] is a dynamic relationship between the interaction force of the robot with the environment and the remote robot's motion error. The impedance control loop generates a modified motion reference x_a. This modified reference is applied to the internal motion loop (see Section 3.4.). The *impedance error* ξ, is defined as follows:

$$\xi = e - [Mp^2 + Bp + K]^{-1} f(t) \tag{9}$$

with, $e = x_L^* - x$ and $M = 0$ for the mobile robot teleoperation case.

3. MOBILE ROBOT CONTROL SYSTEM

3.1. Kinematic equations

We will consider the mobile robot as a unicycle located at a non-zero distance from the objective frame <g> and a frame <a> attached to the robot, as shown in Figure 3.[11]

The kinematic equations of the mobile robot that incorporate the position in the Cartesian system (x, y) and its orientation angle φ are,

$$\begin{cases} \dot{x} = u \cdot \cos \varphi \\ \dot{y} = u \cdot \sin \varphi \\ \dot{\varphi} = \omega \end{cases} \tag{10}$$

where u is the magnitude of the linear velocity vector $\boldsymbol{u}$, and x, y and φ are measured with respect to the origin of the

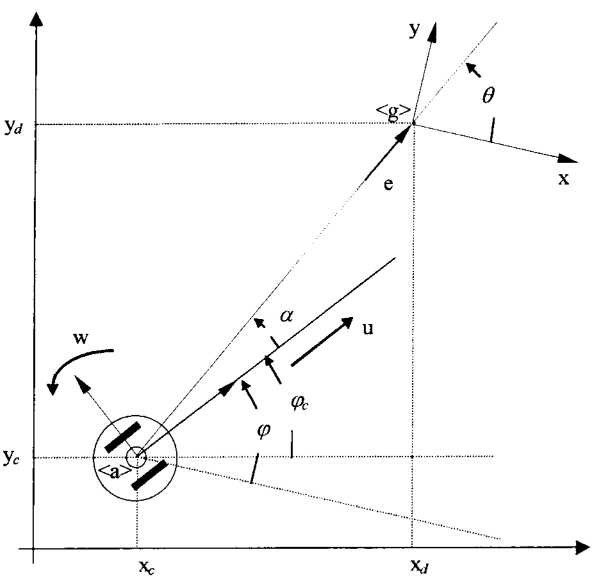

Fig. 3. Position and orientation of the mobile robot.

objective origin frame <g> and the orientation with respect to the axis x of this frame. By considering the vehicle position in polar coordinates and the error vector $\boldsymbol{e}$ with orientation θ respecting the axis x of the frame <g>, and $\alpha = \theta - \varphi$ being the angle measured between the main axis of the vehicle and the vector $\boldsymbol{e}$, the kinematic equations can be re-written as

$$\begin{cases} \dot{e} = -u \cdot \cos \alpha \\ \dot{\alpha} = -\omega + u \cdot \dfrac{\sin \alpha}{e} \\ \dot{\theta} = u \cdot \dfrac{\sin \alpha}{e} \end{cases} \tag{11}$$

3.2. Statement of the problem

The objective of the mobile robot is to reach the frame <g>, considering a desired final orientation. Generally, in the impedance control problem, f is the contact force between the robot and the environment (dynamic relationship between the position error and the interaction force.[5] In this paper, $f(t)$ is considered as a fictitious force, proportional to the distance between the mobile robot and the environment (see Section 3.3).

Therefore, the problem of motion control corresponds to the design of a controller that drives the mobile robot (unicycle vehicle) towards the location of coordinates $e = 0$, $\alpha = 0$ and $\theta = 0$ starting from any non-zero distance from frame <g>. The problem of impedance control incorporates to the controller design the possibility that, after detecting an obstacle in the environment, the robot be capable of modifying its trajectory momentarily in order to avoid such an obstacle.

3.3. Distance sensor feedback

The mechanical impedance regulation needs the feedback of the interaction force between the robot and its environment. The interaction forces imply physical contacts with the environment which, in the case of mobile robots, it means a collision. To avoid obstacles, however, its is necessary to interact with the environment without causing any collision. In such a case, the interaction force $f(t)$ is represented by a fictitious force which depends on the distance between the robot and the obstacle, as shown in Figure 4.

The magnitude of the force $f(t)$ is computed as in references [12], [13] and [14], that is,

$$f(t) = a - b \cdot d(t) \tag{12}$$

where:

a, b	are positive constants, such as $a - b \cdot dmax = 0$;
$Dmax$:	robot-obstacle maximum distance; and
$d(t)$:	robot-obstacle distance $(0 < d(t) < dmax)$.

Figure 5 is the detailed block diagram of the proposed control system for the mobile robot, where, in Cartesian coordinates: x_d is the desired position vector (x_d, y_d, φ_d), x_r is the modified position vector (x_r, y_r, φ_r), ψ is the rotation angle and $\tilde{x}$ is the position error $x_r - x_c$.

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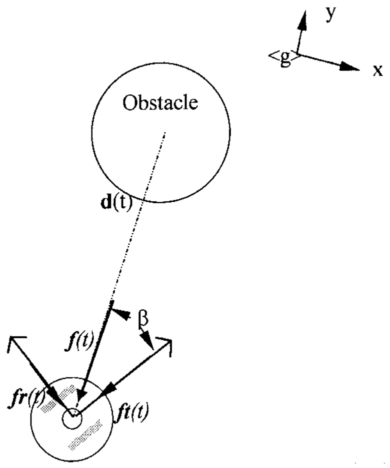

Fig. 4. Action of the fictitious force *f*(*t*) on the mobile robot.

3.4. *Control algorithm*

A typical problem of the controllers is the practical range of the control actions. If this range is not considered in the design, the efficiency of the control system may decrease due to actuator saturation. The present work takes into account this saturation effect and guarantees that the linear velocity u be within the desired fixed range (without saturation).[13]

Motion Control: positioning with orientation. Let the unicycle vehicle be positioned at any non-zero distance from the objective frame <g>, and let e, θ and α, be the state variables that can be measured for any $e>0$. We now consider the Lyapunov's candidate function,[15]

$$V(e,\theta,\alpha)=V_1+V_2=\frac{1}{2}\cdot\lambda\cdot e^2+\frac{1}{2}\cdot\alpha^2+\frac{1}{2}\cdot\kappa\cdot\theta^2 \quad (13)$$

with $\lambda, \kappa>0$. Its time derivative $\dot{V}$ along the trajectory described in equation (11) is given by

$$\dot{V}=\lambda\cdot e\cdot\dot{e}+\alpha\cdot\dot{\alpha}+\kappa\cdot\theta\cdot\dot{\theta} \quad (14)$$

The first term in equation (14), corresponds to $\dot{V}_1$, that can be non-positive when allowing the linear velocity u to have a smooth shape,

$$u=\gamma\cdot\tanh e\cdot\cos\alpha \text{ with } \gamma>0 \quad (15)$$

where $\gamma=|u_{\max}|\cdot$ By regarding the velocity u from equation (15), $\dot{V}_2$ in equation (14) becomes,

$$\dot{V}_2=\alpha\cdot\left(-\omega+\gamma\cdot\frac{\tanh e}{e}\cdot\sin\alpha\cdot\cos\alpha\right)$$
$$+\kappa\cdot\gamma\cdot\theta\cdot\frac{\tanh e}{e}\cdot\sin\alpha\cdot\cos\alpha \quad (16)$$

that may result non-positive if the angular velocity has a smooth shape,

$$\omega=k\cdot\left(\alpha+r\cdot\frac{\theta^2}{\alpha}\right)+\kappa\cdot\gamma\cdot\frac{\tanh e}{e}\cdot\theta\cdot\frac{\sin\alpha}{\alpha}$$
$$\cdot\cos\alpha+\gamma\frac{\tanh e}{e}\sin\alpha\cdot\cos\alpha \quad (17)$$

with $k, r>0$. In equation (17) $|\omega_{max}|=k\cdot(\pi+r\cdot\pi)+\kappa\cdot\gamma\cdot\pi+\gamma\cdot 0{,}5$; and then the following expression is obtained for the time derivate of the original Lyapunov function V

$$\dot{V}=-\lambda\cdot\gamma\cdot e\cdot\tanh e\cdot\cos^2\alpha-k\cdot(\alpha^2+r\cdot\theta^2)<0$$

$$\Rightarrow\begin{cases} e(t) \\ \alpha(t)\rightarrow 0 \text{ when } t\rightarrow\infty \\ \theta(t)\end{cases}$$

This last expression represents a negative defined function. This means that the state variables converge asymptotically to zero, thus meeting the control objective.

The control action of equation (17) cannot be obtained for $\alpha=0$. In order to avoid this problem, a lower bound is proposed for this variable in the first term of equation (17). Now, it is necessary to verify if the stability conditions are met.

By adding and subtracting the term $\left(k\cdot r\cdot\frac{\theta^2}{\alpha_0}\right)$, where $\alpha_0=\delta\cdot\text{sign}(\alpha)$, $\delta>0$, equation (17) can be re-written as,

$$\omega=\omega_0+k\cdot r\cdot\theta^2\left[\frac{\alpha_0-\alpha}{\alpha_0\cdot\alpha}\right]$$

where ω_0 is the expression of equation (17) with α_0 in the first term, and

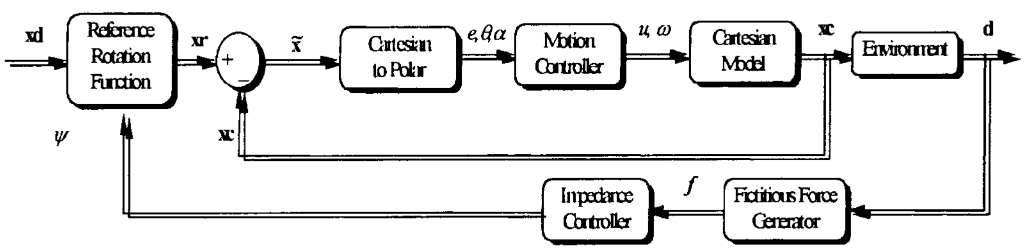

Fig. 5. Block diagram of the proposed mobile robot control system.

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$$\omega = \begin{cases} \omega_0 + k \cdot r \cdot \theta \cdot \left[\dfrac{\alpha_0 - \alpha}{\alpha_0 \cdot \alpha} \right] & \text{if} \mid \alpha \mid \geq \delta \\ \omega_0 & \text{if} \mid \alpha \mid < \delta \end{cases} \tag{18}$$

From equation (18), three cases can be analysed.

Case I: $\mid \alpha \mid \geq \delta$: Here α_0 is equal to α, then,

$$\dot{V}_0 = -\lambda \cdot \gamma \cdot \tanh e \cdot e \cdot \cos^2 \alpha - k \cdot \left(\alpha^2 + r \cdot \theta^2 \cdot \frac{\alpha}{\alpha_0} \right) = \dot{V}$$

which leads to the previously analyzed situation.

Case II: $\mid \alpha \mid < \delta$ and $\alpha \neq 0$: In this case, function $\dot{V}_0$ is,

$$\dot{V}_0 = -\lambda \cdot \gamma \cdot \mathrm{e} \cdot \tanh e \cdot \cos^2 \alpha - k \cdot \left(\alpha^2 + r \cdot \theta^2 \cdot \frac{\alpha}{\alpha_0} \right)$$

Therefore, $0 < \alpha/\alpha_0 \leq 1$, and this implies that $\dot{V}_0$ is negative defined and the control errors converge asymptotically to zero.

Case III: *Evolution of* $\theta(t)$ *when* $\alpha = 0$ *and* $\dot{\alpha} = 0$. In this particular case, $k \cdot r \cdot \theta^2 \cdot \dfrac{\alpha}{\alpha_0} = 0$ the zero convergence of signal $\theta(t)$ is not evident. By applying the LaSalle's theorem:[16]

(i) The system is autonomous.
(ii) There exists a set $\mathbf{S}(e, \theta, \alpha)/\dot{V}_0 = 0$.
(iii) If $\dot{V}_0 = 0$, means that $\alpha(t) = 0$ and $e(t) = 0$. From equations (11) in closed loop,

$$\dot{\theta} = \gamma \cdot \frac{\tanh e}{e} \sin \alpha \cdot \cos \alpha$$

where $\alpha(t) = 0$, $\dot{\theta}(t) = 0$, meaning that $\theta(t) = \text{constant}$.
(iv) The constant value $\theta(t)$ can now be obtained in the set $\mathbf{S}$. From equation (16) in closed loop, where $\alpha(t) = 0$ and $e(t) = 0$, therefore $\dot{\alpha}(t) = 0$, that is,

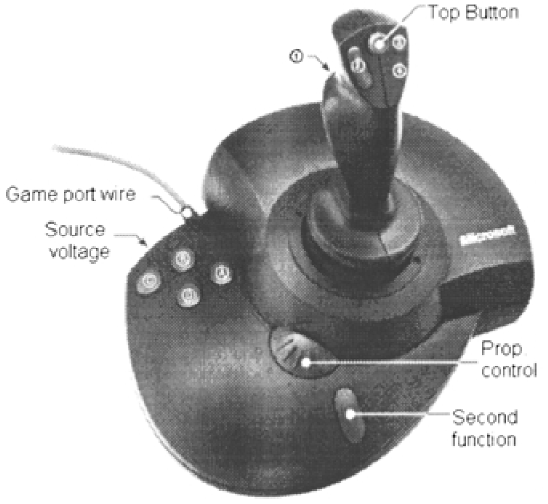

Fig. 6. Microsoft® SideWinder® Forced Feedback Pro Joystick.

$$\dot{\alpha} = -\underbrace{\alpha}_{=0} - k \cdot \frac{\overbrace{\theta^2}^{=ctte}}{\alpha_0} - \kappa \cdot \gamma \cdot \overbrace{\theta^2}^{=ctte}$$

$$\cdot \underbrace{\frac{\tanh e}{e}}_{=1} \cdot \underbrace{\frac{\sin \alpha}{\alpha}}_{=1} \cdot \underbrace{\cos \alpha}_{=1} = 0$$

It may be concluded that $\theta = 0$ in $\mathbf{S}$. By following LaSalle's theorem, the control errors asymptotically converge to zero. The control objective is guaranteed when the control actions are bounded.

Impedance Control. The desired impedance is defined as,[14]

$$Z = Bs + K$$

and,

$$x_a = Z^{-1} \cdot f_t \tag{19}$$

where: B, K are positive constants and f_t is the component of f (fictitious force) in the robot motion direction.

Based on Figure 4, it is regarded that, $\psi = x_a \cdot sign(f_r)$, where f_r is the component of f (fictitious force) normal to the robot's motion direction. Then, the transformation,

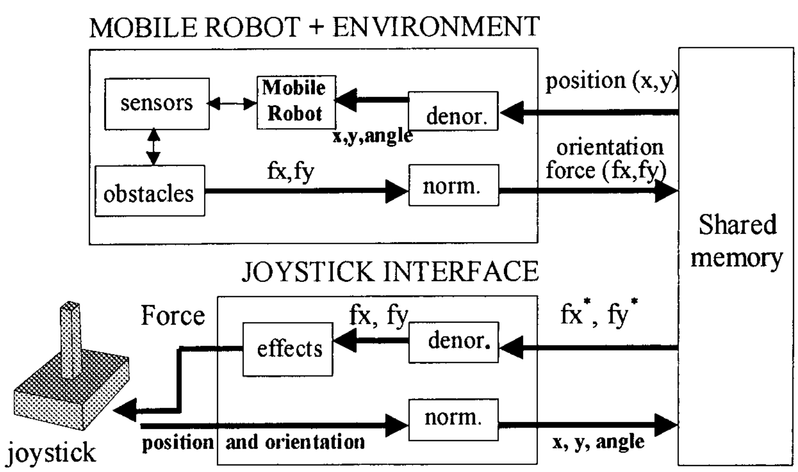

Fig. 7. Developed interface and the shared memory.

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$$\mathbf{x_r} = \begin{bmatrix} \cos\psi & \text{sen}\,\psi & 0 \\ -\text{sen}\,\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{x_d}$$

is applied and the position error is computed as,

$$\tilde{x} = x_r - x_o$$

When the fictitious force is zero, $x_r = x_d$, and the motion control objective is met, it means that $\tilde{x} \to 0$ with $t \to \infty$.

4. JOYSTICK FOR ROBOT TELEOPERATION

When performing a teleoperation task, the remote robot should be supplied with the information and commands for its desired motion. The joystick sends this information, depending on the applied teleoperation structure but independently of the communication channel used. These signals may be the references for the remote control system.[1,17,19]

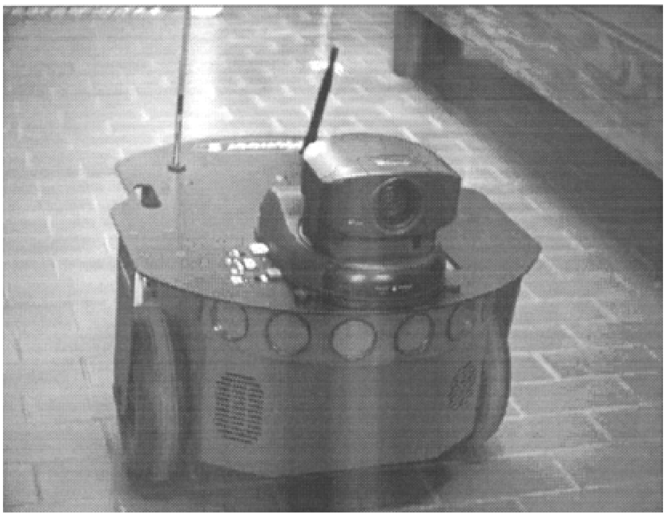

Fig. 8. PIONEER 2 mobile robot.

One of the most popular devices used, as a master robot in robotic teleoperation systems is the force-feedback joystick (*ffj*) which allows the human operator "to feel" the interaction force between the remote robot and the obstacles in its environment. The force feedback compounded with the visual feedback lets the teleoperation tasks be more versatile and increase the sensation of presence of the human operator at the remote site[17–19] besides, completing their main objective as reference generators of orders to the remote mobile robot.

The joystick used in this work is a Microsoft® SideWinder® Forced Feedback Pro, shown in Figure 6. It has a top button that allows controlling the direction of the mobile robot, a graduate control and, besides the conventional motions in axes x and y, it can rotate in z-axis.

An interface application to communicate, this joystick with the remote mobile robot was developed as a Visual C++ application.[19,20] It uses the functions of the applications programming interface (API) called Microsoft® DirectInput™, that in turn, is a component of Microsoft® DirectX™. DirectInput is a set of functions in charge of optimizing the communication between input devices and their drivers. This feature allows the programmers to provide to the applications with a quick and efficient access to such devices. As it was mentioned before, both stations (local and remote) of the teleoperation system use a *shared memory* to read and to write the data transferred between them.

Shared memory. If two or more applications have to share information, they must accede to a file stored in the disk and write or read the information in it. This method is slow, and it is more critics if the applications that need to share data run in real time. The shared memory is used to solve these

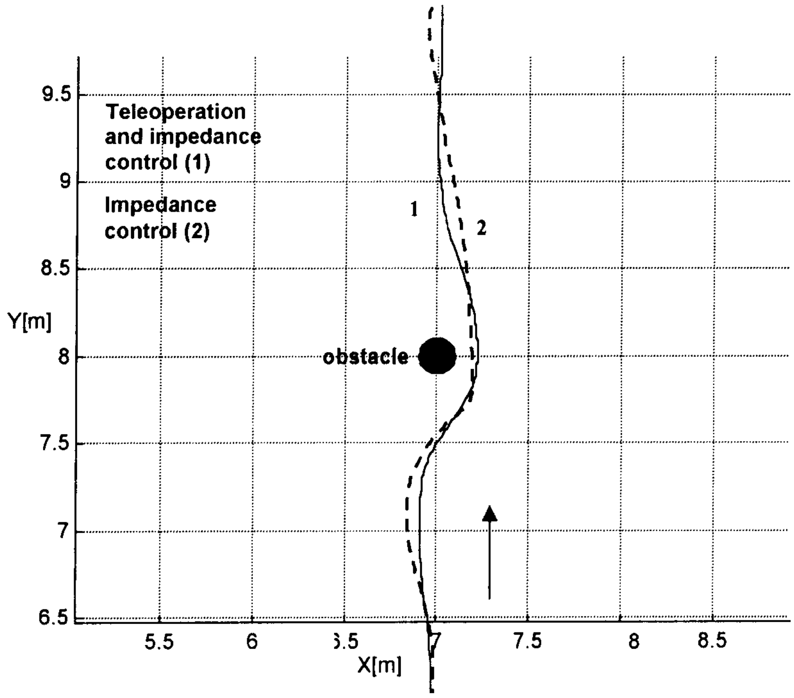

Fig. 9. Experiment 1: Mobile robot trajectory.

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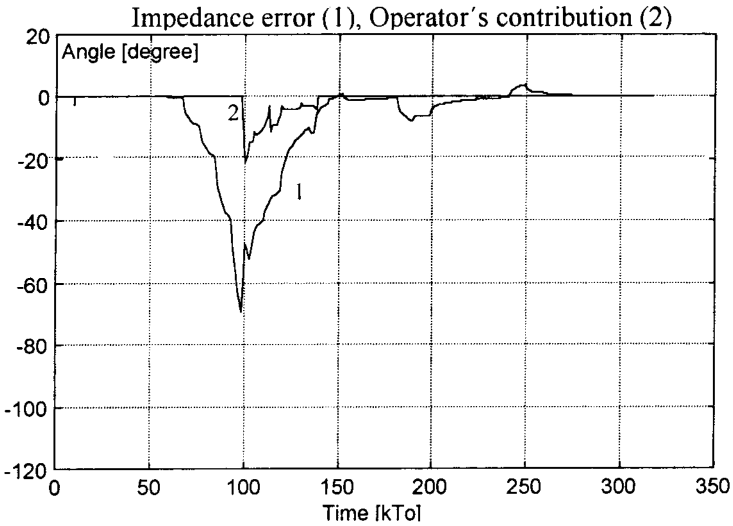

Fig. 10. Experiment 1: Impedance error and operator's contribution.

kind of problems. The shared memory is a memory block that two or more applications may use to read and to write their data. This memory block is treated by the applications as a file stored in disk, but with the advantage that, as it is memory location, the access is much faster. This way, it is possible to speed up the data transfer from one application to the other.

Joystick interface. The interface is the application in charge of adapting the force feedback joystick to the implemented control system for mobile robot teleoperation. The interface functions are to: accede the joystick, to read the position of their axes, to normalize these data, to write them in the shared memory block so that they are received by the other application (the remote mobile robot), to read the shared memory data that are sent from the mobile robot, to denormalize the received data, and from them, to execute the effects of force on the joystick, etc. Figure 7 is a block diagram of the elements acting in both applications.

5. EXPERIMENTAL RESULTS

To illustrate the effectiveness, performance and stability of the proposed control structure for mobile robot teleoperation, experiments have been conducted on a PIONEER 2DX mobile robot (Figure 8). The joystick used for the teleoperation was described in Section 4.

In the experiments, only tactile feedback was used for the teleoperation system and the visual information is used only to guide the human operator, this means $(1-\rho)=0$ in equation (1). The parameters used for the desired impedance are: K=8 N/rad and B=0.5 N.sec/rad. It should be noticed that the impedance control loop is active when the mobile robot detects an obstacle at a distance less than 1.5 m.

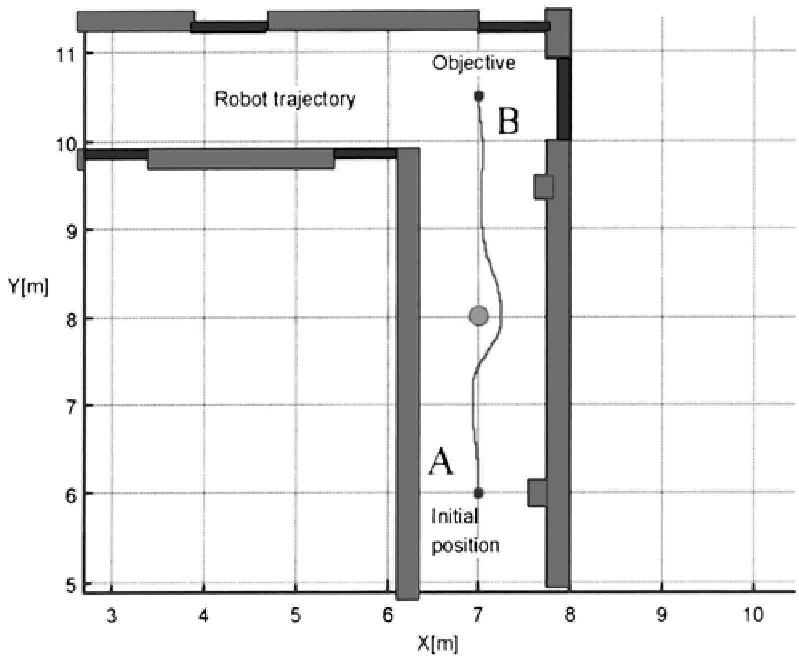

Fig. 11. Experiment 2: Mobile robot trajectory.

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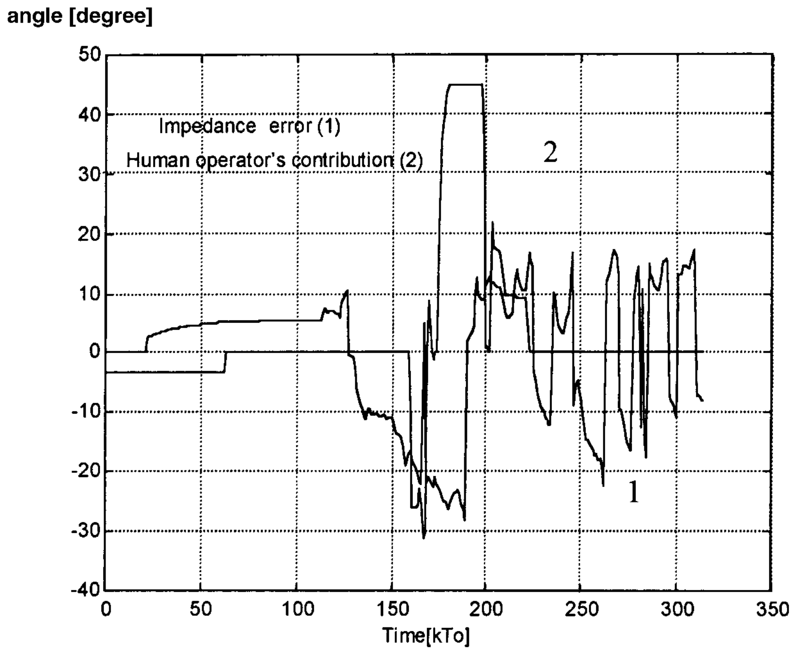

Fig. 12. Experiment 2: Impedance error and operator's contribution.

In the first experiment, Figure 9 shows the mobile robot trajectories, only with impedance control and while being teleoperated (including the impedance controller) in an environment with an obstacle. Figure 10 depicts, separately, both the impedance error of the proposed control structure, and the contribution of the joystick, through the human operator's action, to the mobile robot teleoperation task. After analysing at both figures, it can be concluded that the mobile robot motion is better when a teleoperation control structure is used. It yields a smooth motion trajectory and a good teleoperation performance, because the human operator adjusts with his/her on-line contributions to the proposed controller when unknown-shape obstacles appear on the desired trajectory of the mobile robot.

In the second experiment, Figure 11 shows the mobile robot trajectory, when it is being teleoperated in an environment with obstacles, from an initial point A, to a destination point B, along an aisle inside INAUT's building. Figure 12 depicts, separately, both the impedance error of the proposed control structure, and the contribution of the joystick, through the human operator's hand, to the mobile robot teleoperation task. In Figures 12 and 13, the oscillations in the impedance error evolution and in the fictitious force, respectively, are due to a strong interaction

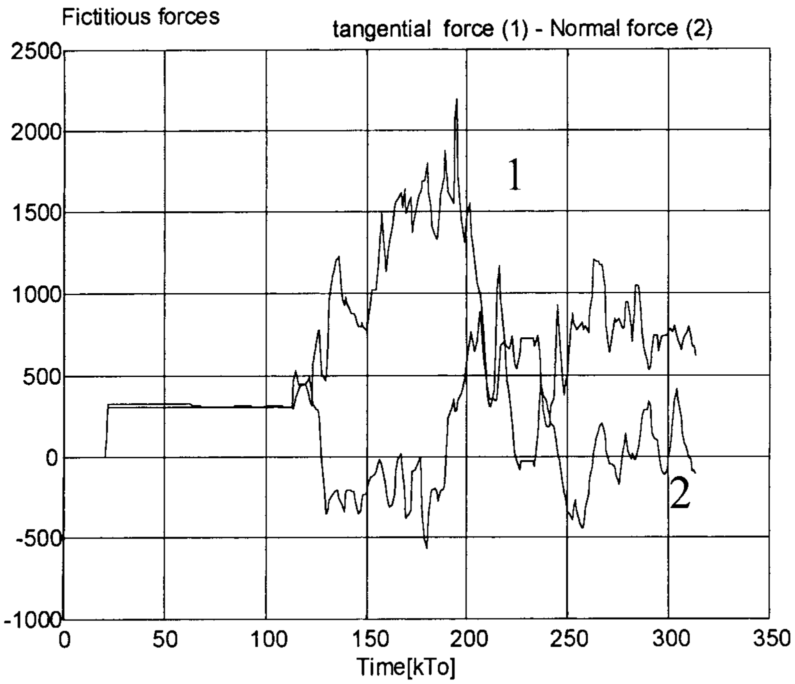

Fig. 13. Experiment 2: Fictitious forces on the mobile robot.

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and proximity between the ultrasonic sensor array of the mobile robot and the aisle walls. Nevertheless, the performance of the teleoperation control structure is not degraded because the contribution of the human operator to the teleoperation task is significant.

The fictitious forces exerted on the mobile robot platform, obtained from the distance measurement of the ultrasonic sensors, are shown in Figure 13.

6. CONCLUSIONS

In this paper, a simple and effective control structure for mobile robot teleoperation is proposed. The proposed strategy combines an impedance control loop for mobile robot obstacle avoidance (in the remote station) with a teleoperation scheme including tactile and visual feedback of the interaction force of the mobile robot with its environment to the human operator (in the local station). The teleoperation structure includes in the local station a simplified model of the human operator.

The proposed control structure is based on external sensor information, provided by ultrasonic sensors. This sensor information is used both by the impedance controller and by the teleoperation system, for the generation of a fictitious force, which is a function of the sensed distance between the mobile robot and the obstacle in the trajectory.

The stability analysis of the control system has been presented. Several experiments with a PIONEER 2DX mobile robot platform and a commercial joystick, for its teleoperation, were carried out to test the proposed control structure. The experiments show a good performance and a stable behaviour of the whole teleoperation system. Also, experiments clearly depict the important contribution of the human operator to the control actions, when executing teleoperation tasks, which allows smoothing the mobile robot's trajectory and to better the teleoperation system performance when interacting with partially known environments. From these results, we may conclude that the application of the proposed controller in an industrial telerobotic system is feasible.

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